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Hydrodynamic Time Scales and Temporal Structure of GRBs

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We calculate the hydrodynamic time scales for a spherical ultra-relativistic shell that is decelerated by the ISM and discuss the possible relations between these time scales and the observed temporal structure in γ-ray bursts. We suggest that the bursts' duration is related to the deceleration time, the variability is related to the ISM inhomogeneities and precursors are related to internal shocks within the shell. Good agreement can be achieved for these quantities with reasonable, not fined tuned, astrophysical parameters. The difference between Newtonian and relativistic reverse shocks may lead to the observed bimodal distribution of bursts' durations.

INTRODUCTION

Gamma-ray bursts (GRBs) are most likely generated during deceleration of ultra-relativistic particles. A cosmological compact source that emits the energy required for a GRB cannot generate the observed non thermal burst. Instead it will create an opaque fireball (see e.g. (1,2)). If even a small amount of baryonic matter is present then the ultimate result of this fireball will be a shell of ultra-relativistic particles (3). The kinetic energy can be recovered as radiation only if these particles are decelerated by the ISM (4) or by internal shocks (5,6). We show that a careful analysis of the interaction between the ultra-relativistic particles and the ISM changes some of the previous results and sheds a new light on the expected temporal structure in GRBs.

PLANAR SYMMETRY

Consider a slab of ultra-relativistic cold dense matter with a Lorentz factor $\gamma \gg 1$ that hits a stationary cold interstellar medium - the ISM. Two shocks form: a reverse shock that propagates into the dense relativistic shell, reducing its speed and increasing its internal energy, and a forward shock that propagates into the ISM giving it relativistic velocities and internal energy. A contact discontinuity separates the shocked shell material and the shocked ISM.

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There are two limits (7) in which the reverse shock is either Newtonian or ultra-relativistic (the forward shock is always ultra-relativistic in our case). We define f as the density ratio of the ultra-relativistic shell and the ISM . If $\gamma^2 \gg f$ the reverse shock is ultra-relativistic. In this case:

$$\gamma_2 = \gamma^{1/2} f^{1/4}/\sqrt{2} \;\; ; \;\; t_\Delta = \Delta\gamma\sqrt{f}/2c \; , \tag{1}$$

where γ_2 is the Lorentz factors of the shocked material (shocked material on both sides of the contact discontinuity move at the same velocity) relative to an observer at infinity, Δ is the width of the ultra-relativistic shell and t_Δ is the time that the reverse shock crosses the shell. Since $\gamma_2 \ll \gamma$, almost all of the initial kinetic energy is converted by the shocks into internal energy. Therefore the process is over after a single passage of the reverse shock through the shell, and the relevant time scale for energy extraction is the shell crossing time, t_Δ. Along the contact discontinuity the energy densities are equal and since both shocked regions have comparable width they release comparable amounts of energy. The ISM mass swept by the forward shock at the time that the reverse shock crosses the shell is $\sim f^{-1/2}$ of the shell's mass. This is larger than the simple estimate given by Mésźaros, & Rees (4) of $\sim \gamma^{-1}$.

If $f \gg \gamma^2$ the reverse shock is Newtonian and:

$$\gamma_2 \cong \gamma \;\; ; \;\; t_\Delta = \sqrt{9/14}\Delta\gamma\sqrt{f}/c \tag{2}$$

Since now $\gamma_2 \cong \gamma$ the reverse shock converts only a small fraction, $\gamma/\sqrt{f} \ll 1$, of the kinetic energy into internal energy and t_Δ is no longer the relevant time scale for energy extraction. The main deceleration is during a quasi-steady state in which the shell decelerates continuously without shocks. The slowing down time can be estimated by $\sim \Delta f/c\gamma$. During this time the forward shock collects a fraction $\sim \gamma^{-1}$ of the shell's rest mass, which is the same as the original estimate of Mésźaros & Rees (4). In contrary to the relativistic case, there are two time scales now: the shock crossing time, t_Δ, and the total slowing down time, t_γ.

In the realistic situation the ISM density is probably inhomogeneous. Consider a density jump by a factor f' over a distance l_{ISM}. The forward shock propagates into the ISM with a density n_1 as before and when it reaches the position where the ISM density is $n_1 f'$ a new shock wave is reflected. This shock is reflected again of the shell. Similar analysis shows that the reflections time is $\sim l_{ISM}/4c\sqrt{f'}$.

Finally, we mention the possibility of internal shocks inside the shell (5). These may form when faster material overtakes slower material. If the Lorentz factor varies by a factor of ~ 2 over a length scale $\delta R \leq \Delta$ then the time for these shock to from is $\sim \delta R\gamma^2/c < \Delta\gamma^2/c$. This time scale is shorter than the slowing-down time scale and therefore internal shocks appear before considerable deceleration in the Newtonian case. In the relativistic case considerable deceleration occurs before internal shocks unless $\delta R \ll \Delta$.

SPHERICAL CONSIDERATIONS

In a spherical system the density ratio $f \sim R^{-2}$ decreases with time. Initially $f/\gamma^2 \gg 1$ and the reverse shock is Newtonian. The energy conversion depends critically on the question whether this shock become relativistic before the kinetic energy is extracted from the shell. This depends, in turn, on the ratio of two radii: $R_N = l^{3/2}/\Delta^{1/2}\gamma^2$ where $f/\gamma^2 = 1$ and the reverse shock becomes relativistic and $R_\Delta = l^{3/4}\Delta^{1/4}$ where the reserve shock crosses the shell. The radius $l \equiv (E/n_1 m_p c^2)^{1/3}$ in these expressions is the Sedov length which is familiar from SNR theory. Two other important radii are: $R_\gamma = l/\gamma^{2/3}$ where the forward shock sweeps a mass M/γ (M is the shell's rest mass) and $R_s = \Delta\gamma^2$ where the shell begins to spread if the initial Lorentz factor varies by order γ (1). Note that R_s is also an upper limit for the the location of internal shocks since $\delta R < \Delta$. Conveniently, the four critical radii are related by one dimensionless quantity:

$$\xi \equiv (l/\Delta)^{1/2}\gamma^{-4/3} \quad ; \quad R_N/\xi = R_\gamma = \sqrt{\xi}R_\Delta = \xi^2 R_s \ . \tag{3}$$

Two possibilities exist:

1. $\xi > 1$ - the Newtonian case: $R_s < R_\Delta < R_\gamma < R_N$ and shock reaches the inner edge of the shell while it is still Newtonian. Most of the energy is extracted during a steady state deceleration phase within the radius R_γ. Since R_s is smaller than all other radii spreading might be important. If the shell is spreading then Δ in the above expressions should be replaced by R/γ^2. This delays the time at which the reverse shock reaches the shell and decreases the shell's density. These effects lead to a triple coincidence: $R_\Delta = R_\gamma = R_N$ with $\xi \approx 1$ and a mildly relativistic reverse shock during the period of effective energy extraction. Without spreading only a small fraction of the total energy is converted to thermal energy in the reverse shock. With spreading both shocks convert comparable amounts of energy.

2. $\xi < 1$ - the relativistic case: $R_N < R\gamma < R_\Delta < R_s$. The reverse shock becomes relativistic before it crosses the shell. Only a small fraction of the energy is converted at R_γ and the kinetic energy is converted into internal energy only at R_Δ. R_s is larger than all other radii and spreading is unimportant. It is interesting to note that in this limit $\gamma_2(R_\Delta) \sim (l/\Delta)^{3/8}$ is independent of the initial Lorentz factor γ and it is only weakly dependent on other parameters. This might have an important role in the fact that the observed radiation always appears as low energy γ-rays.

Neither the internal shocks nor the ISM inhomogeneity time scales are affected by these spherical considerations. The former depends only upon δR, Δ and γ and the latter depends only on l_{ISM} and γ. Both are constant throughout the spherical expansions.

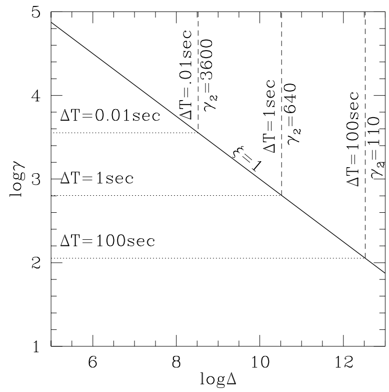

FIG. 1. The observed duration of the burst (dotted curve in the Newtonian regime and dashed curve in the relativistic regime) as function of γ and Δ for $l = 10^{18}$cm. The thick line ($\xi = 1$) separates the Newtonian (lower left) and the Relativistic (upper right) regions. Spreading drives all Newtonian cases to the $\xi \approx 1$ line.

OBSERVATIONAL IMPLICATIONS TO GRB

We examine now the possible relation between the observed time scales and the hydrodynamic time scales. We assume that the shocked material emits the radiation on a time scale shorter than the hydrodynamic time scales. A simple estimate of synchrotron cooling rate (assuming equipartition of the magnetic field energy) is consistent with this assumption. The requirement that the cooling time is shorter than the observed variability imposes interesting constraints on the physical conditions within the shocks. In particular it demands that the turbulent magnetic field within the shocked material should be very close to equipartition with the thermal energy there. We discuss these conditions elsewhere (8).

While the value of $l \approx 10^{18}$cm is known (Using $E = 10^{51}$ergs and $n_1 = 1$particle/cm^3), the values of Δ and γ are more ambiguous. Using the canonical values (2) $\gamma = 10^3$ and $\Delta = 10^7$cm we get $\xi \cong 30 > 1$, corresponding to a Newtonian reverse shock. Nevertheless a value of $\xi \cong 0.1 < 1$ is also possible with reasonable parameters (for example $\Delta = 10^9$cm and $\gamma = 10^4$). Therefore, both relativistic and Newtonian reverse shock are possible.

The bursts' duration is determined by the slowing down time of the shell divided by γ_2^2. Thus, given a typical radius of energy conversion, R_e the observed time scale is:

$$\Delta t_{obs} = R_e/\gamma_2^2 c = \begin{cases} \Delta/c & \text{if } \xi < 1 \quad \text{(Relativistic);} \\ R_\gamma/\gamma^2 c \sim l/\gamma^{8/3} c & \text{if } \xi > 1 \quad \text{(Newtonian)} \end{cases} . \tag{4}$$

Δt_{obs} ranges from $\sim$ 1msec, for $\Delta = 3 \times 10^7$cm and $\gamma = 10^4$, to $\sim$ 100sec for $\gamma = 10^2$ and $\Delta = 10^{13}$cm (see fig. 1). The observed durations of the brightest

30 bursts limit γ to $100 < \gamma < 10^4$ with a typical value of ≈ 500 and it limits Δ to $\Delta < 3 \times 10^{12}$cm.

A possible source of the observed fluctuations during the bursts is inhomogeneity in the ISM. If the length scale of the inhomogeneity is l_{ISM} and the density varies by one order of magnitude then the time scale for the observed variability will be:

$$t_{var} \sim l_{ISM}/10\gamma_2^2 c \ . \tag{5}$$

Clearly, t_{var} can be sufficiently short if l_{ISM} is sufficiently small.

Precursors which appear in about 3% of the bursts might be explained by internal shocks that take place at $R \approx \delta R\gamma^2 \leq \Delta\gamma^2$ while the main burst originates from the interaction with the ISM. The duration of the precursor is $\Delta t_{pre} = \Delta/c$, which requires values of Δ as high as $10^{10} - 10^{12}$cm to produce the observed precursors of $1 - 100\,$sec. If $\xi > 1$ the main bursts will have a duration $\Delta t_{obs} \approx l/\gamma^{8/3}c = \xi^2\Delta$. This will also be the typical separation $\Delta t_{pre-maim}$ between the precursor and the main burst. We expect a time delay between the precursor and the main burst which will be comparable to the duration of the main burst. Note that a correlation of the form $\Delta t_{pre-maim} \approx 4.5\Delta t_{obs}$ exists (but was not reported) in the data of Koshut *et. al.,* (9). If $\xi < 1$ then precursors do not occur (unless $\delta R \ll \Delta$). This is in agreement with the lack of observed precursors in short bursts.

CONCLUSIONS

We have calculated the hydrodynamic time scales of shocks during the interaction between an ultra-relativistic shell and the ISM. We find that with reasonable astrophysical parameters these time scales are in a good agreement with the observed time scales in GRBs. Our analysis shows that there are two kinds of shocks: Newtonian and Relativistic. The difference between them might correspond to the observed bimodality of short and long bursts. Finally, we suggest that precursors might be emitted due to internal shocks within the ultra-relativistic shell while the main burst emerges later from the interaction with the ISM.

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